

# Laser Sounder Approach for Measuring Atmospheric CO<sub>2</sub> from Orbit

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**Abstract-** We describe progress in developing a laser-based approach for the remote measurement of atmospheric CO<sub>2</sub> from a satellite in low earth orbit. In this method, CO<sub>2</sub> abundance is measured by differential absorption in an overtone band near 1.57  $\mu\text{m}$ . The dry-air mixing ratio can be calculated from the ratio of CO<sub>2</sub> to O<sub>2</sub>, which can be measured using a similar technique applied to an O<sub>2</sub> absorption at 770 nm. A third channel operating at 1.064  $\mu\text{m}$  will be used for cloud and aerosol detection. The approach leverages technology development by the telecommunications industry, using mainly commercially available components, many of which have already been space qualified. Measurement precision better than 1% will be needed to satisfy the scientific requirements. Component stability and noise levels must therefore be thoroughly investigated. In addition, a rigorous calibration strategy will be required. We report initial atmospheric measurements over a horizontal path and results from tests to characterize individual components.

## I. INTRODUCTION

Mounting concern regarding the possibility that increasing carbon dioxide concentrations will initiate climate change has stimulated interest in the feasibility of measuring CO<sub>2</sub> mixing ratios from satellites. Currently, the most comprehensive set of atmospheric CO<sub>2</sub> data is from the NOAA CMDL cooperative air sampling network, consisting of more than 40 sites where flasks of air are collected approximately weekly [1]. Sporadic observations in the troposphere and stratosphere from airborne in situ and flask samplers are also available [2 - 4]. Although the surface network is extensive, there is a dearth of data in the Southern Hemisphere and most of the stations were intentionally placed in remote areas, far from major sources. Sufficiently precise satellite observations with adequate spatial and temporal resolution would substantially increase our knowledge of the atmospheric CO<sub>2</sub> distribution. Current estimates indicate that a measurement precision of better than 1% will be needed in order to improve estimates of carbon uptake by land and ocean reservoirs [5, 6].

Several potential techniques for measuring CO<sub>2</sub> from space are under development. We propose a laser sounder [7] instrument using the differential absorption technique for measuring CO<sub>2</sub> abundance near 1.57  $\mu\text{m}$  and O<sub>2</sub> near 770 nm. The ratio of CO<sub>2</sub> to O<sub>2</sub> will provide a measurement of the dry-air mixing ratio of CO<sub>2</sub>. This quantity should be

insensitive to fluctuations in surface pressure resulting from changing

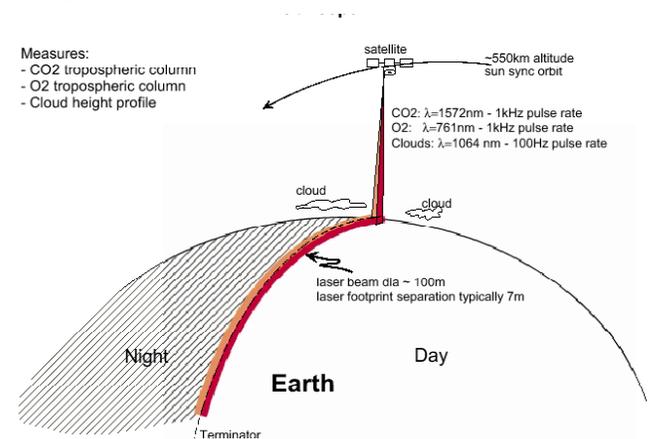


Figure 1. Proposed Laser Sounder Measurement Scenario Concept

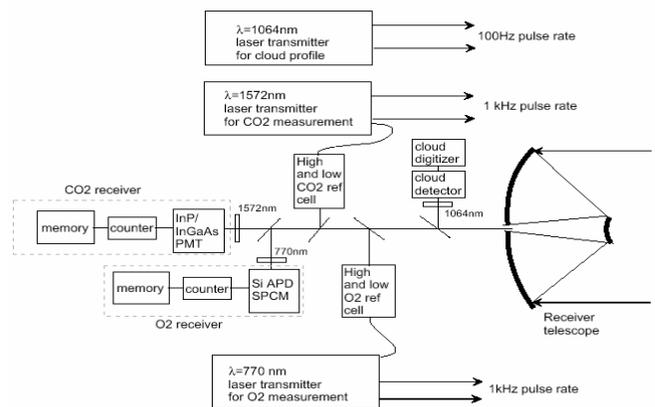


Figure 2. Proposed Laser Sounder Instrument Diagram

topography or weather systems and to fluctuations in humidity. A third channel at 1.064  $\mu\text{m}$  will detect clouds and aerosols in the sample footprint. Figure 1 shows a schematic view of the measurement scenario concept and the instrument diagram is shown in Figure 2. An important advantage of our active (laser-based) technique over passive approaches is that measurements can be made at any time of day. CO<sub>2</sub> is known to have large diurnal variations near the surface, and biases may result from aliasing of these daily

fluctuations. We plan to select a dawn-dusk orbit that would provide measurements near the maximum and minimum daily values.

Vertically resolved CO<sub>2</sub> profiles are highly desirable, but with available technologies, total column measurements may prove more feasible in the next decade. Our approach measures laser light reflected from Earth's surface and thus provides a column-integrated quantity. However, some profile information may be obtained by observing a spectral line at multiple frequencies of varying optical depth. Figure 3 shows the vertical weighting of the column-integrated absorption corresponding to different points along the line. Pressure broadening provides enhanced sensitivity to lower altitudes in the line wings. This property can be exploited to isolate the variability in the lower atmosphere.

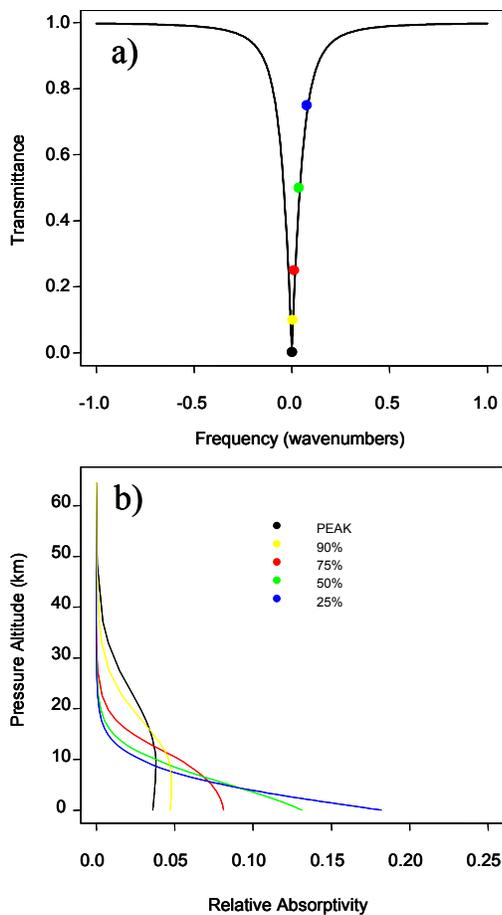


Figure 3. a) Calculated transmittance for a spectral line centered near 1.57 μm corresponding to a 2-way path from a satellite to earth and back. b) Vertical weighting functions for several points along the line. The colors correspond to the points in Figure 2a.

Previous efforts to develop laser-sounder long-path instruments for atmospheric CO<sub>2</sub> measurement include work at the 4.88 μm [8] and 2 μm [9] wavelengths. We selected the spectral region near 1.57 μm based on several criteria.

The spectral band consists of discrete narrow lines that are free from interference due to water vapor and other trace atmospheric constituents (Figure 4). The optical depths are strong enough to provide high sensitivity to changes in CO<sub>2</sub> amount, but are not so strong as to be saturated. In addition, this wavelength falls within the telecommunications “L-Band” extending from 1.57 - 1.61 μm. We can therefore leverage a substantial commercial research and development effort focused on improving components in this wavelength region. Single-frequency, narrow linewidth, distributed feedback (DFB) semiconductor lasers are available for the 1.57 μm transmitter. These low power lasers will seed Erbium Doped Fiber Amplifiers (EDFA's) to generate the high powers needed for operation from orbit. Similar seed lasers will be used with frequency doubling in the transmitter for the O<sub>2</sub> channel at 770 nm. The similarity of the O<sub>2</sub> and CO<sub>2</sub> transmitters is a major advantage of our technique over other active methods, since there are no other convenient sources of laser light at 770 nm that are suitable for space flight.

Receiver components are also commercially available at this wavelength. Photomultiplier tubes with adequate sensitivity and noise characteristics are currently available, and new detector technologies, such as avalanche photodiodes, are under development. Many receiver optical components, including a 1m telescope, have been developed and space qualified for the Geoscience Laser Altimeter System (GLAS) on ICESat (Ice, Cloud and land Elevation Satellite), currently in orbit [10].

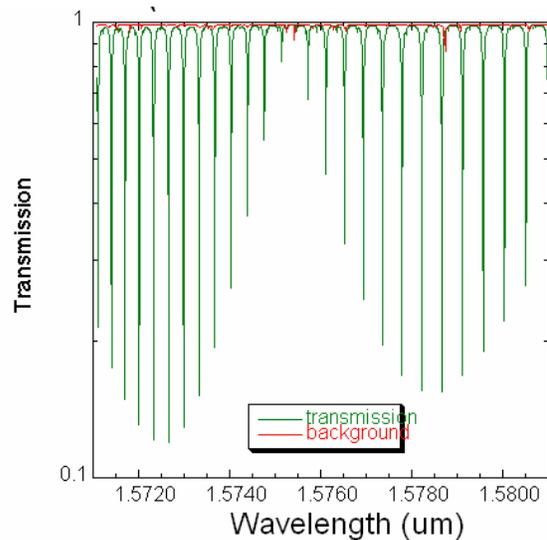


Figure 4. Transmittance for a 1-way path between the surface and space for the band of CO<sub>2</sub> absorption lines centered near 1.57 μm. Also shown is the “background” transmission (i.e., the transmission for all species other than CO<sub>2</sub>), which shows the absence of interference from other species.

## A. With laser diode alone

The line parameters in the 1.57  $\mu\text{m}$  wavelength region have recently been studied in detail for pure CO<sub>2</sub> using diode-laser spectroscopy [11]. We validated these results with similar measurements using a diode laser transmitter and a 36 meter path-length multipass gas-cell filled with pure CO<sub>2</sub>. Figure 5 is a plot of the experimentally measured transmission (open crosses) at  $\sim 13.3$  KPa (100 Torr) and  $\sim 23$  C°. The overlaid dashed-curve is a HITRAN generated Voigt profile for similar experimental conditions. Compared to the data HITRAN slightly over-predicts the saturated transmission at line center. The open circles represent a Lorentzian fit to the data. A Levenberg-Marquardt algorithm is used to determine a least squares set of coefficients that best fits a Lorentzian, frequency-dependent absorption coefficient extracted from the Lambert-Beer's Law transmission. The measured Lorentzian broadening parameter agrees with the predicted broadening from HITRAN and is 2.98 MHz/mbar. [12].

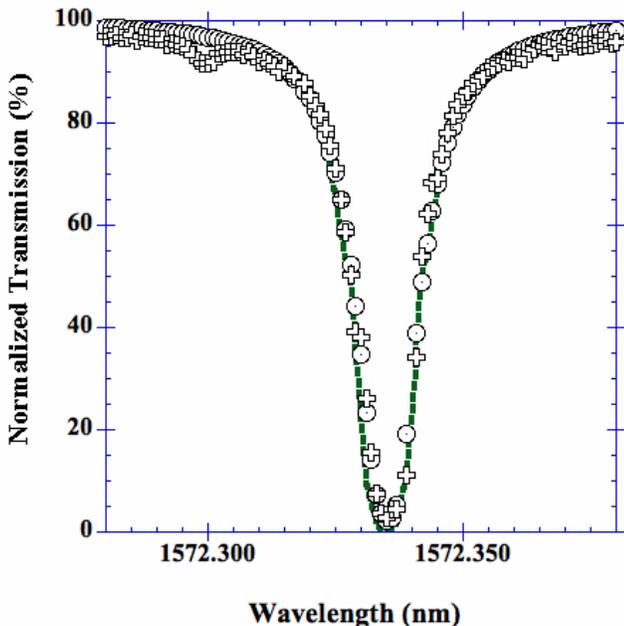


Figure 5. Scan over saturated CO<sub>2</sub> absorption line using unamplified tunable diode laser.

## B. With laser diode amplified by erbium fiber amplifier

As shown in Figure 6, we verified that the quality of the CO<sub>2</sub> absorption line spectra is preserved when the laser diode is amplified by a high-power erbium fiber amplifier operating at its maximum (5 W) output power.

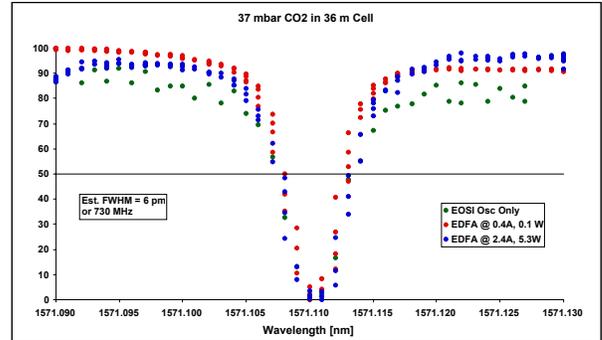


Figure 6. Scan over CO<sub>2</sub> absorption using diode laser amplified with an EDFA at 3 different optical power output levels.

 IV. LONG-PATH ATMOSPHERIC CO<sub>2</sub> MEASUREMENTS

We have recently begun making measurements of ambient CO<sub>2</sub> over a long horizontal path [13]. Our experimental setup is shown in Figure 7. The tunable-diode-laser (New Focus Model 6330) wavelength is scanned over a CO<sub>2</sub> absorption line at a rate of 200 Hz with a triangular wave from a signal generator. The laser output is fed through a 40 dB optical isolator to a high-power (5 W) erbium-doped fiber-optic-amplifier (IPG Photonics Model EAD-5) and directed through a custom transmitting telescope (1.5 mradian beam divergence). The light then traverses an open air path ( $206 \pm 4$  meter one-way at an average 10 m altitude) to a hard target reflector (0.7 m x 0.7 m flat aluminum plate covered with Moco Model V82 Conspicuity Reflexite Tape) and retro reflected back to the receiver telescope (20 cm Meade). At the receiver, custom optics focus the light on to a 1 mm diameter InGaAs PIN detector (New Focus Model 2034). To improve the sensitivity for longer path measurements, we will replace the PIN detector with a near-infrared photomultiplier tube [14]. The detector/pre-amplifier output is band-limited to 3 kHz and digitized (NI Model PCI-MIO-16E-1 12 bit A/D) at a rate of 100 ksamples/s. The resulting transmission plot is shown in Figure 8. Also shown is the theoretical prediction from the HITRAN database (for a 206 m one-way path length and an atmospheric CO<sub>2</sub> concentration of 415 ppm as measured simultaneously by a Licor Model LI-6262 CO<sub>2</sub> Analyzer, see below for more details). The experimental data was scaled to match the calculated transmission, assuming differences were due to a DC offset on the detected signal. A calculated DC offset of 0.25 (transmission units) provides the best fit to the theory.

A simple algorithm [15] to process and retrieve CO<sub>2</sub> concentration in real-time is given by:

$$CO_2 ppm = K \ln \left[ \frac{1}{N} \sum_{i=1}^N \left( \frac{S_{ON}}{S_{OFF}} \right)_i \right] \quad (1)$$

where  $K$  is a calibration constant (determined by making a one-time independent  $\text{CO}_2$  measurement),  $S_{ON}/S_{OFF}$  is the measured transmission ratio (ON at 1572.335 nm and OFF at 1572.260 nm), and  $N$  is the number of measurements over the spectral line.

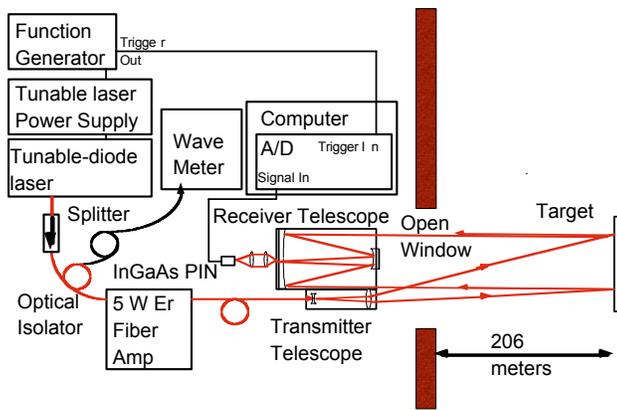


Figure 7. Laboratory prototype atmospheric  $\text{CO}_2$  measurement diagram.

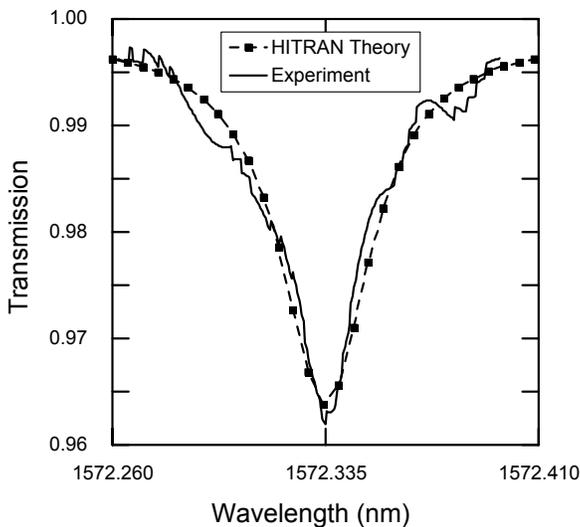


Figure 8. HITRAN theory and measured ( $N=2000$ ) atmospheric transmission at NASA Goddard Greenbelt, MD for 206 m one-way path on 11/21/02 at 4:50 PM EST. The experimental data have been adjusted to provide the best fit to the theory (see text for details).

Using this differential absorption algorithm, we measured the  $\text{CO}_2$  concentration every 10 seconds ( $N=2000$ ). The data were referenced and scaled to match the Li-cor measurement at a single point. Data from the prototype laser sounder and the Li-cor analyzer remained correlated within  $\pm 1$  ppm over 6 hours as shown in Figure 9. With the current setup, nighttime data are of higher quality than daytime observations. This is because we have not yet incorporated a reference path in our prototype instrument to compensate for system changes and the system is most stable during non-work hours.

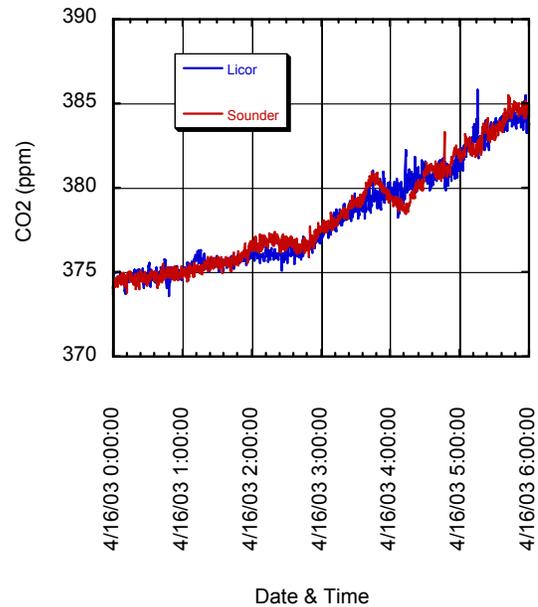


Figure 9. Li-cor analyzer point measurement and prototype Laser Sounder column measurement comparison.

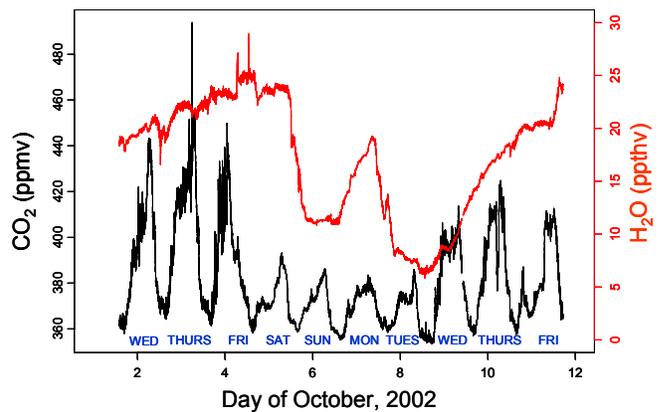


Figure 10. Data from the Li-cor 6262  $\text{CO}_2/\text{H}_2\text{O}$  Analyzer obtained from the roof of our building at NASA GSFC in Greenbelt, MD.

## V. $\text{CO}_2$ MEASUREMENT VALIDATION

A commercial in situ sensor for measuring  $\text{CO}_2$  and  $\text{H}_2\text{O}$  (LI-6262  $\text{CO}_2/\text{H}_2\text{O}$  Analyzer, Li-cor Biosciences, Lincoln, NE) has been equipped with pressure and flow control and computer control for automated calibration. Air is drawn into the sensor in the laboratory through a tube on the roof. The Li-cor analyzer serves as a tool for validating our horizontal path measurements. The data shown in Figure 10 provide an indication of the typical diurnal cycle present in  $\text{CO}_2$  mixing ratios measured at GSFC. The diurnal variability likely reflects some combination of plant activity, atmospheric mixing, and local pollution. GSFC is

located near the intersection of the Washington Beltway (I-495) and the Baltimore-Washington Parkway (MD 295). However, there is also considerable wooded area on the GSFC campus and in surrounding areas. Since the Li-cor analyzer samples at a point near the building, while the laser sounder samples a round trip path 412 m in length from the laboratory window, there is some question as to whether the measurements are directly comparable. To facilitate validation of our technique, we have recently acquired a 300m multipass cell (Aerodyne Research Inc., Billerica, MA). In a future experiment, air will be drawn in from the roof through the multipass cell and then into the Li-cor analyzer. Light from the laser transmitter will be fiber-coupled into the multipass cell and then into the receiver.

## VI. COMPONENT TECHNOLOGY

### A. Laser Transmitter

As noted, we choose to work at the CO<sub>2</sub> overtone band at 1.57 μm that falls within the telecommunication L-band in order to leverage the world-wide industry investment in the associated laser and electro-optic technology. Our laser transmitter concept is shown in Figure 11. A timing diagram is shown in Figure 12 optimized to ensure comparable signal to noise ratios for each wavelength.

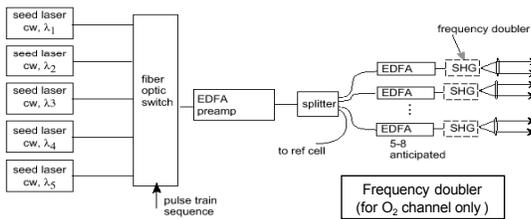


Figure 11. Laser sounder transmitter design for CO<sub>2</sub> and O<sub>2</sub> channels based on specifications for Lucent EDFA's.

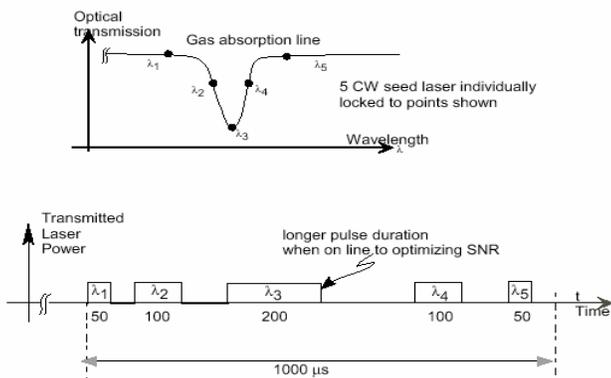


Figure 12. Laser Sounder laser transmitter timing diagram for CO<sub>2</sub> channel. Pulse widths are defined by the optical depth at each wavelength.

Distributed feedback semiconductor laser diodes are readily available with narrow spectral linewidth. Commercial fiber optic amplifiers with up to 20 W optical power have

recently been introduced by IPG Photonics. In addition, Lucent has developed a 10 W space qualified erbium fiber amplifier (Figure 13) with the specifications listed below.

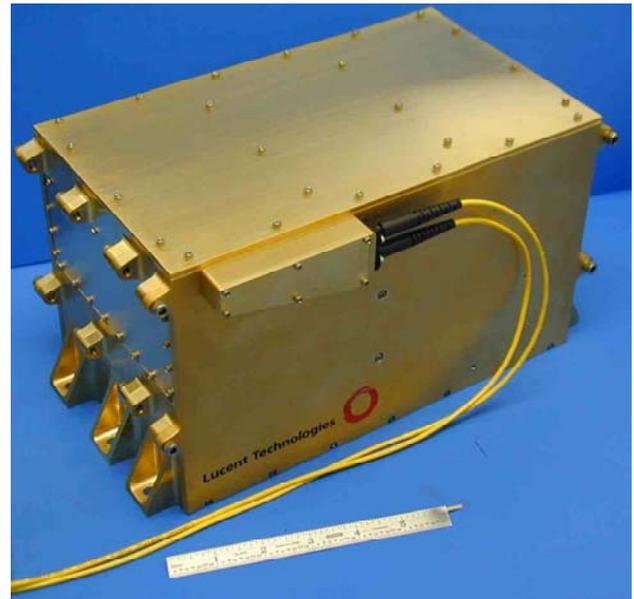


Figure 13. Lucent 10 W space-qualified erbium fiber amplifier.

Lucent space-qualified erbium-fiber-amplifier specifications	
Average optical power	10 W
Typical optical input power	0dBm to 10dBm
Optical tuning range:	1550nm to 1565nm
Wall-plug efficiency	6.3%
Baseplate operating temperature	0 °C to 40 °C
Size:	0.3 ft <sup>3</sup>
Weight:	19 lbs
Power supply:	20VDC to 34VDC
Control and telemetry	RS-422

Table 1. Lucent 10 W space-qualified fiber amplifier specifications.

### B. Photon Counting detector

We tested a commercial InAlAs/InGaAs photomultiplier (Hamamatsu Model R5509-72) that will be incorporated into our prototype laser sounder instrument in the near future. This work is summarized in [14] with the highlights reviewed here. We measured a photon counting efficiency of 1.5% at 1550 nm wavelength at a dark count rate of 130,000 cps when cooled to -80 °C with 1500 V applied. The output pulse width was measured to be 4 ns with a dead time between adjacent pulses measured to be limited by the pulse width. We achieved an SNR of 540 at an input signal level of 46 net detected signal photons (3200 incident photons) per laser pulse after averaging over 50,000 pulses.

Encouraged by recent photon counting results [15], we are also investigating the use of InGaAs avalanche photodiodes as our detector.

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